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ON TIDAL VARIATION OF GRAVITY

BY

Ichiro NAKAGAWA

1. Introduction

Change of gravity with time is generally divided into two branches. Namely, one is a periodic variation and the other non-periodic. The former is a phenomenon caused by the tide-generating forces due to the sun and the moon, and it is usually referred to as "tidal variation of gravity". The latter is regarded to be related with rapid or gradual change of gravity caused by change of state or motion of the underground material, the fluctuation of rotation speed of the earth, the crustal deformation and the like.

Now, let the tide-generating potential at any point on the earth due to a celestial body be denoted by W_2. According to the theory, if the earth is perfectly rigid, the quantity Δg of the tidal variation of gravity at its point is expressed by

$$\Delta g = \left(\frac{\partial W_2}{\partial r}\right)_{r=a}, \tag{1}$$

where r is the radius vector from the earth centre and a the mean radius of the earth. However the real earth is a finite elastic body and consequently yields by action of the tide-generating force. Such being the case, the value Δg of the tidal variation of gravity on the real earth is

$$\Delta g = G \cdot \left(\frac{\partial W_2}{\partial r}\right)_{r=a}, \tag{2}$$

$$G \equiv 1 - \frac{3}{2}k + h, \tag{3}$$

where h and k are dimensionless constants called "Love's numbers". h is related with the radial displacement of the earth's surface caused by deformation of the earth, and k the change of potential field caused by the same cause. Love's numbers, h and k, are closely correlated with the rigidity and density distributions within the earth. And the symbol G is usually called "tidal factor of gravity" or, in short, "gravimetric factor".

On the other hand, the value of D which is called "diminishing factor" can be obtained from a tiltmetric observation or observation of the oceanic tides.

Diminishing factor D is expressed by the formula

$$D \equiv 1 + k - h . \qquad (4)$$

Consequently, if the values of G and D are determined from observations, the numerical values of Love's numbers, h and k, can easily be determined, without any assumption on the density and elasticity distributions of the earth's interior, by combining (3) with (4).

Since the first observation of earth tides with a gravimeter of the bifilar suspension type by W. Schweydar (1), a great many observations have been made at various regions of the world. However, the values of the tidal factor of gravity obtained by these observations show divergency of wide range from 0.8 to 1.3. As the value of the tidal factor of gravity is closely correlated with rigidity and density distributions of the earth's interior, it is expected to show the same value wherever or whenever the observation be carried out. It is therefore considered that the diversity in the obtained tidal factor of gravity is due to disturbances of some causes. For the causes of such a diversity, the following may be considered, that is, position of the observation station, effect of the oceanic tides, influence of the local geological structure, effect of the meteorological disturbances, difference of the instrument used in observation, difference in time of observation, difference in length of observation period, methodical difference in treating the data, and others. A thorough investigation for these causes is an essential and attractive problem on the gravimetric study of earth tides.

In the following, a detailed consideration concerning these points is described, transcribing from the present author's articles (2, 3, 4, 5, 6) written under a title of "Some Problems on Time Change of Gravity".

2. Observational results

The instrument used in the present observations was an Askania Gs-11 gravimeter No. 111 (7) equipped with an automatic recording apparatus, its sensitivity being nearly 2.5 μgal/mm on the registrogram. The speed of motion of the recording paper was 8 mm/hour and time-marks were recorded at every hour with an accuracy of ± 30 seconds. Before and after the observation at each station, the gravimeter was precisely calibrated, and it was confirmed that there was no noticeable time change in scale constant of the gravimeter.

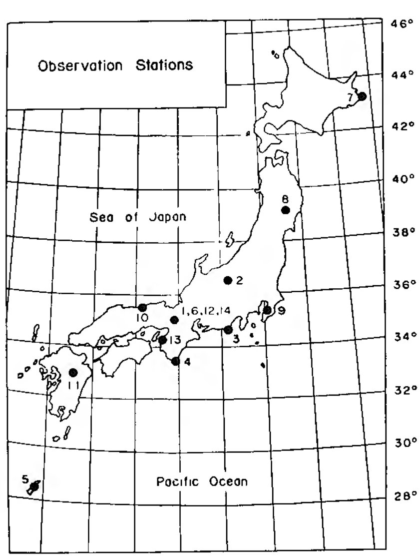
The observation stations were mainly selected from two standpoints of both the distance from the effective sea and the gravity anomaly, and they were shown in Table 1 and Fig. 1.

Observations were consisted of two branches; one was one month's observation and the other one year's observation. The former was carried out at eleven stations in Japan during a period of about two years from July 1957 to May 1959 (International Geophysical Year), for the purpose of investigating a diversity in

Table 1. Description of the observation stations

Station number	Observation station	Location			Gravity anomaly (mgal)	Distance from the effective nearest sea (km)	Remarks
		Latitude (N)	Longitude (E)	Height (m)			
1	Kyoto (I)	35°02′	135°47′	57.8	− 14	50	M
2	Matsushiro	36 32	138 13	434.0	− 10	170	M
3	Omaezaki	34 36	138 13	45.5	+ 52	0.5	M
4	Shionomisaki	33 27	135 46	74.2	+139	0.4	M
5	Naze	28 23	129 30	3.3	+100*	0.08	M
6	Kyoto (II)	35 02	135 47	59.9	− 14	50	M
7	Nemuro	43 20	145 35	25.1	+222	0.7	M
8	Mizusawa	39 08	141 08	60.7	+ 69	50	M
9	Kanozan	35 15	139 58	350.5	+ 6	9	M
10	Tottori	35 30	134 14	20	+ 17*	5	M
11	Aso	32 53	131 01	567	− 16*	40	M
12	Kyoto (II)	35 02	135 47	59.9	− 14	50	Y

Notes: The distance between Kyoto (I) and Kyoto (II) is about 300 meters.
The values with asterisk are tentatively assumed.
M: One month's observation Y: One year's observation



1. Kyoto (I)
2. Matsushiro
3. Omaezaki
4. Shionomisaki
5. Naze
6. Kyoto (II)
7. Nemuro
8. Mizusawa
9. Kanozan
10. Tottori
11. Aso
12. Kyoto (II)
13. Wakayama
14. Kyoto (II)

Fig. 1 Positions of the earth tidal observation station the tidal factor of gravity caused by difference of observation station, and the latter was carried out continuously at Kyoto during a period of about one year from August 1959 to August 1960, for the purpose of investigating that caused by difference in time of observation.

Reading of registrograms was made at every hour up to 0.1 mm. Drift curve

Table 2. Values of G and κ

One month's observation

Station number	Central epoch (UT)	M_2		S_2		K_1		O_1	
		G	κ	G	κ	G	κ	G	κ
1	July 14, 18h, 1957	1.143	−1.°12	1.096	−3.°91	1.065	+ 0.°68	1.163	+0.°21
2	Sept. 10, 18h, 1957	1.128	−0. 89	1.103	+1. 97	0.900	+19. 40	1.005	+2. 62
3	Oct. 24, 18h, 1957	1.239	−2. 15	1.259	−1. 73	1.600	−16. 99	1.289	+6. 35
4	Feb. 3, 18h, 1958	1.141	−0. 23	1.079	−4. 99	1.121	− 8. 66	1.074	+0. 46
5	Apr. 16, 18h, 1958	1.197	−3. 24	1.150	−4. 57	1.007	+22. 89	1.272	−7. 41
6	June 27, 18h, 1958	1.115	−1. 24	1.204	−1. 32	1.037	− 1. 41	1.011	−1. 28
7	Aug. 17, 18h, 1958	1.191	+0. 36	1.132	+2. 23	1.264	+ 0. 30	1.343	−2. 31
8	Oct. 1, 18h, 1958	1.110	+1. 73	1.076	−3. 58	1.130	+ 2. 26	1.146	−0. 88
9	Nov. 15, 18h, 1958	1.180	+0. 55	1.313	−3. 16	1.497	−20. 58	1.124	−5. 13
10	Feb. 23, 18h, 1959	1.161	−6. 44	1.093	+8. 45	1.642	−24. 70	1.170	−5. 95
11	May 4, 18h, 1959	1.128	−2. 70	1.198	−3. 58	1.090	+ 3. 29	1.064	−3. 92

One year's observation at Kyoto

Analysis number	Central epoch (UT)	M_2		S_2		K_1		O_1	
		G	κ	G	κ	G	κ	G	κ
1	Aug. 24, 00h, 1959	1.144	−1.°07	1.070	+ 5.°03	1.087	− 1.°22	1.017	+ 0.°22
2	Sept. 14, 00h, 1959	1.132	−2. 12	1.135	+ 4. 16	1.498	+ 8. 60	1.427	+ 1. 94
3	Oct. 5, 00h, 1959	1.123	−5. 21	1.154	+ 5. 58	1.368	− 1. 05	1.240	−15. 33
4	Oct. 26, 00h, 1959	1.149	−3. 01	1.083	+10. 72	1.194	− 2. 21	1.119	+ 0. 91
5	Nov. 16, 00h, 1959	1.137	−3. 37	1.047	+ 9. 75	1.188	− 3. 00	1.027	− 1. 92
6	Dec. 7, 00h, 1959	1.164	−1. 70	1.089	+11. 15	1.214	− 2. 96	1.287	− 3. 16
7	Dec. 28, 00h, 1959	1.147	−2. 15	0.995	+ 4. 71	1.285	− 5. 93	1.220	− 0. 13
8	Jan. 18, 00h, 1960	1.157	−1. 99	1.028	+ 0. 86	1.317	− 5. 78	1.232	− 0. 05
9	Feb. 8, 00h, 1960	1.145	−1. 61	1.113	+ 1. 88	1.177	− 6. 47	1.155	+ 0. 25
10	Feb. 29, 00h, 1960	1.130	−2. 34	1.089	− 7. 36	1.257	− 5. 62	1.150	+ 0. 34
11	Mar. 21, 00h, 1960	1.162	−1. 57	1.088	+ 0. 83	1.134	−11. 08	1.126	+ 1. 89
12	Apr. 11, 00h, 1960	1.177	−0. 83	1.085	+ 3. 13	0.896	− 3. 24	1.231	− 8. 78
13	May 2, 00h, 1960	1.144	−0. 79	1.062	+ 0. 39	1.011	+ 1. 78	1.203	+ 2. 41
14	May 23, 00h, 1960	1.150	−1. 71	1.082	− 1. 13	1.023	+ 0. 18	1.263	+ 5. 62
15	June 13, 00h, 1960	1.092	−1. 61	1.188	+ 3. 83	1.025	+ 0. 10	1.190	+ 1. 16
16	July 4, 00h, 1960	1.130	−3. 82	1.099	+ 1. 80	1.087	+ 2. 42	1.197	− 2. 95
17	July 25, 00h, 1960	1.147	−3. 20	0.900	+ 7. 28	1.111	+ 3. 26	1.153	+ 1. 57

of the gravimeter was, first of all, eliminated by Pertzev's method (8) and a harmonic analysis was made by Lecolazet's method (9) with the help of an electronic computing machine 'IBM-650'.

The tidal factor of gravity G and phase lag κ for four principal tidal constituents thus obtained are shown in Table 2 with epoch of the analysis. Here, the positive sign of κ shows that the observed tide advances the theoretical one, while the negative sign shows the former lags behind the latter.

During the gravimetric tidal observations, room temperature and pressure variations were also observed. These data during the corresponding periods were analysed harmoniously as well as the gravimetric data.

3. Discussion

Although results of harmonic analysis are obtained for four major tidal constituents, the succeeding discussion is restricted to M_2-constituent which is the most trustworthy among these constituents and is the largest at a region of medium latitudes such as Japan. The values of G and κ for M_2-constituent are considerably diverse due to both difference of the observation station and that of the observation time, as can easily be seen from Table 2.

In one month's observations, what is regarded to have the most important effect upon the tidal factor of gravity are the oceanic tides. Their effect is generally consisted of three principal parts. The first is the effect of vertical component of the gravitational attraction by the tidal change of sea water; the second, the effect of elastic deformation of the solid earth due to the tidal load of sea water; and the third, the effect caused by distorsion of the potential field due to deformation by the tidal load.

The first influence can be calculated by use of a cotidal chart of the oceanic waters (10). The vertical component of attraction with M_2-period arising from the tidal variation of oceanic water within a range of radius of 1°, is shown in Table 3, the observation station being its centre.

As for the second influence, the Nagaoka's formula (11) on the elastic deformation of ground by surface load, is theoretically applicable. But in a practical case, the calculation is exceedingly troublesome. Regarding the third influence, no satisfactory theory so as to calculate its amount is known up to the present.

Conveniently, in the present case, the experimental formula which is the most fitting the observational results, is examined. Practically the observed tides are separated into two terms, that is, one the primary component G_0 not disturbed by the oceanic tides and the other the second component which is effect of the oceanic tides.

Table 3. The vertical component of attraction by M_2-constituent of the oceanic tides

Station number	Vertical attraction (μgal)
1	$0.001 \cos (2t+167.6^\circ)$
2	$0.002 \cos (2t+279.0)$
3	$0.791 \cos (2t+197.0)$
4	$1.690 \cos (2t+185.4)$
5	$0.116 \cos (2t+160.3)$
6	$0.001 \cos (2t+167.6)$
7	$0.189 \cos (2t+254.5)$
8	$0.002 \cos (2t+244.6)$
9	$0.243 \cos (2t+210.4)$
10	$0.005 \cos (2t+299.2)$
11	$0.104 \cos (2t+110.7)$
12	$0.001 \cos (2t+167.6)$

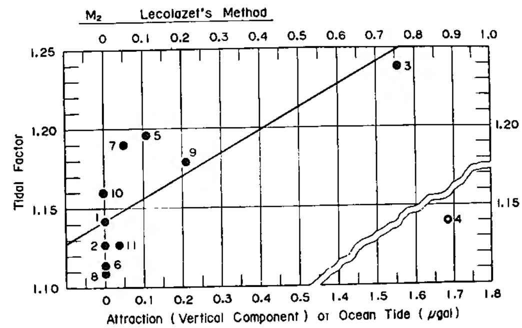


Fig. 2 Relation between the tidal factor of gravity and the vertical component of attraction by tidal water. (One month's observation)

In Fig. 2 is shown the relation between the vertical component of attraction by the tidal water and the tidal factor obtained by harmonic analysis. In this figure, all points are seen to be in a line except one for Shionomisaki (4). Let d be the correction factor for drift-elimination introduced by the author (3, 12), its value being 0.99934 in the present case. Assuming

$$d \times \text{Observed tide} = G_0 \times \text{Theoretical tide} + a \times \text{Vertical tide}, \qquad (5)$$

G_0 (the tidal factor of gravity in Japan free from influence of the oceanic tides) and a (correction factor for the oceanic tides) can be obtained by method of the least square using the observational results of ten stations except Shionomisaki. The values of G_0 and a thus obtained are as follows:

$$\left.\begin{aligned} G_0 &= 1.142 \pm 0.011, \\ a &= 7.5 \pm 2.2. \end{aligned}\right\} \qquad (6)$$

On the other hand, in one year's observation, there are diversities, even for M_2-constituent, by about 8% in tidal factor of gravity and by about 5° in phase lag during a year in spite of the observation at one station with the same gravimeter, as can easily be seen from Table 2. As for the cause concerning the time change in values of the tidal factor of gravity and phase lag obtained at one station, it is suspected that an observational error, disturbance caused by meteorological changes, real time change of those values and others are probably responsible, and that the disturbance caused by meteorological changes is probably dominant. Assuming then

$d\times$Observed tide

$$=G'\times\text{Theoretical tide}+\gamma\times\text{Temperature component}+\delta\times\text{Pressure component}, \quad (7)$$

G' (the most probable tidal factor of gravity free from the influence of temperature and pressure variations), γ (correction factor for temperature variation) and δ (that for pressure one) can be obtained by method of the least square using the observational results. The values of G', γ and δ thus obtained are as follows:

$$\left.\begin{aligned} G'&=1.138\pm0.005\,, \\ \gamma&=-17\pm8\,\mu\text{gal}/^{\circ}\text{C}\,, \\ \delta&=-3.9\pm1.7\,\mu\text{gal/mmHg}\,. \end{aligned}\right\} \quad (8)$$

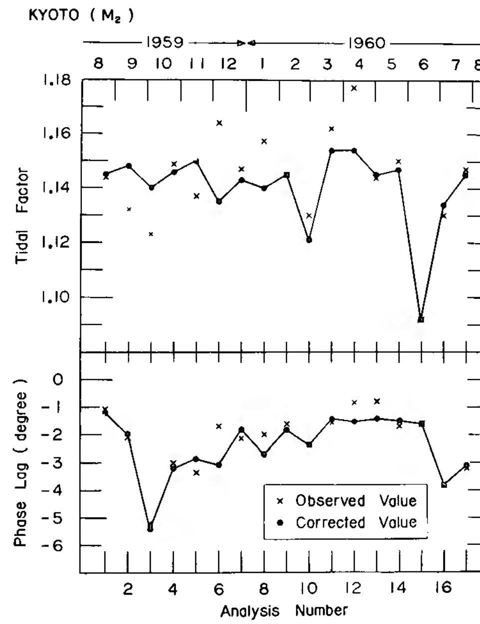


Fig. 3 Tidal factor of gravity and phase lag. (One year's observation)

Since influence of the oceanic tides is negligibly small at Kyoto' the value of G' thus obtained may be considered as the one free from the influence of the oceanic tides' Corrected values of the tidal factor of gravity and phase lag for M_2-constituent thus obtained are shown in Fig. 3 with the observed ones.

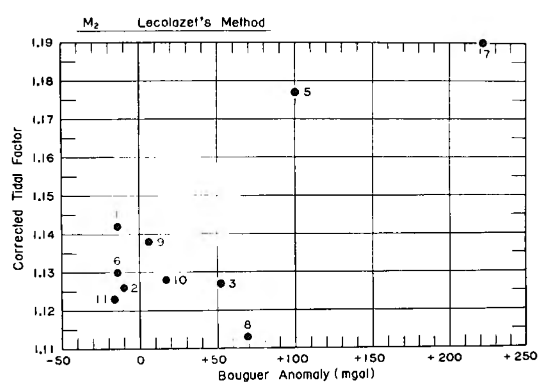


Fig. 4 Relation between the corrected tidal factor of gravity and Bouguer anomaly. (One month's observation)

The mean values of the tidal factor of gravity and phase lag are as follows:

$$\left.\begin{aligned} G(M_2)&=1.138\pm0.005\,, \\ \kappa(M_2)&=-2.^{\circ}40\pm0.^{\circ}28\,. \end{aligned}\right\} \quad (9)$$

It is therefore concluded from Fig. 3 that there are differences, concerning M_2-constituent, by 3% in tidal factor of gravity and by 4° in phase lag during a year, if the influence caused by temperature and pressure variations is excluded from the obtained values.

Using the correction factors a, γ and δ above-obtained, the analytical results for M_2-constituent obtained by one month's observations can be corrected for influences of the oceanic tides, temperature and pressure variations. The relation between the corrected tidal factor of gravity and Bouguer anomaly is shown in Fig. 4. In view of this figure, a certain relation seems to be existing between the corrected tidal factor of gravity and Bouguer anomaly.

4. Conclusion

From these considerations mentioned above, the following conclusions are obtained.

(1) If the influences caused by the oceanic tides, temperature and pressure variations are excluded from the observed values, a sufficiently reliable result can be obtained by one month's observation so far as M_2-constituent is concerned.

(2) The most reliable values of the tidal factor of gravity and phase lag for M_2-constituent in Japan, free from influences of the oceanic tides, temperature and pressure variations, are as follows:

$$G(M_2)=1.14 \quad \text{and} \quad \kappa(M_2)=-2^\circ . \qquad (10)$$

The value of the tidal factor of gravity obtained above is in good agreement with that obtained at some stations in Asia (13), but it is far smaller than the tidal factor of gravity in Europe or that of theoretical investigations (14, 15, 16) on earth tides. The difference between the observational results in Asia and those in Europe is clearly recognized in both tidal factor of gravity and phase lag. A thorough investigation for the cause of its difference is a very interesting and attractive problem.

5. Appendixes

1. Gravity observation during a period of annular eclipse

The problem of a screening effect of gravitational force caused by a third body interposing between two attracting bodies, is an exceedingly interesting one, and therefore this problem has been discussed both theoretically and experimentally. A solar eclipse is a good opportunity to investigate experimentally this problem.

Observations with a gravimeter to investigate the screening effect of gravitation during a solar eclipse, were carried out by some researchers (17, 18, 19). According to their conclusion, the effect was about 2~3 μgal, if it existed.

An annular eclipse occurred over some scattered islands in the south regions of the Main Land of Japan on April 19, 1958, and Naze was situated in the annular eclipse zone. The gravimetric observation at Naze was carried out continuously during a period of 42 days from March 29 to May 10, 1958 by means of the Askania gravimeter No. 111 with an automatic recording apparatus at an old seismograph room of Naze Weather Station for the purpose of observing the tidal variation of gravity at a solitary island in the Pacific Ocean and investigating whether the solar attraction was screened by the moon interposed at the time of the annular eclipse. The gravity change was recorded with a speed of 20 mm/hour, and sensitivity of the gravimeter was 2.5489 μgal/mm.

Reading of the records obtained during seven days around the eclipse day, was made at 10-minute intervals up to 0.1 mm. After influences of temperature and pressure variations, the instrumental drift and tidal waves were excluded from all the read values, a residual curve and its smoothed one were obtained. Results obtained for three days around the eclipse day were shown in Fig. 5.

In this figure, there is no obvious difference between the eclipse and ordinary periods. There exist always disturbances with a period of one to three hours on the smoothed residual, and their amplitude amounts to about 2~3 μgal. It is therefore concluded that the screening effect of gravitation, even if it exists, during the present solar eclipse does not exceed 3 μgal.

This conclusion is in perfect agreement with that obtained by R. Tomaschek (17) and others (19). Since there exist disturbances with an amplitude of 2~3 μgal in the ordinary period, it seems to be insignificant to discuss in further detail the screening effect of gravitation.

In order to elucidate the gravitational absorption due to the earth's mass itself, the author (20) is now calculating by use of data obtained by one year's observation.

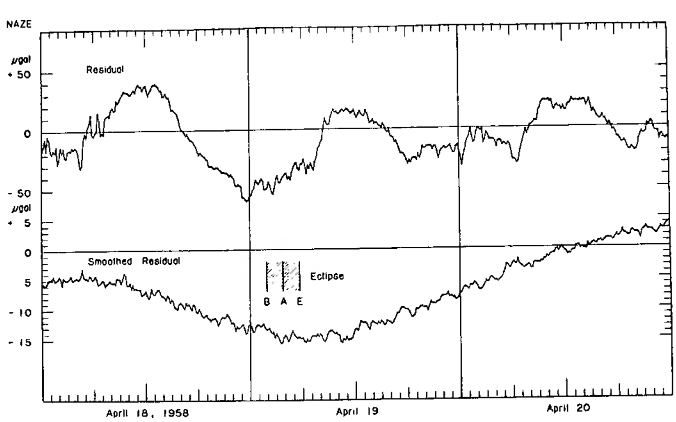


Fig. 5 Residual and smoothed residual during three days around the eclipse day.

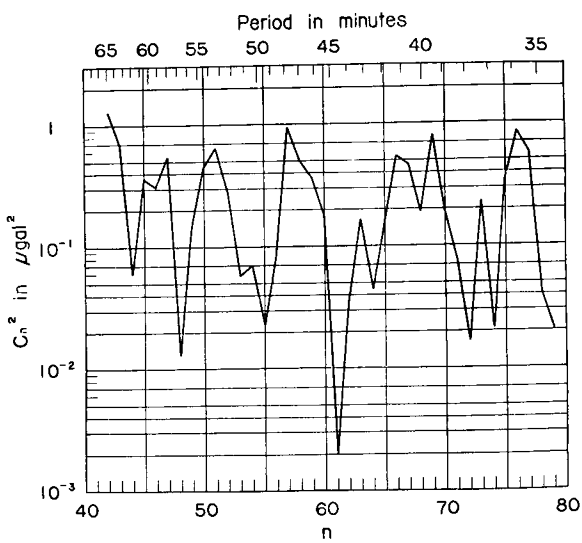


Fig. 6 Smoothed power Cn^2 for periods of 65–35 minutes.

2. Free oscillations of the earth

A theoretical investigation on free oscillations of the earth has been made since the latter part of the nineteenth century. On the contrary, an observation of the free oscillations of the earth was carried out by H. Benioff (21, 22) alone at the time of the Kamchatka earthquake on November 4, 1952. But the free oscillations of the earth excited by the great Chilean earthquake on May 22, 1960 were observed in America (23, 24, 25, 26) and Europe (27, 28), and their existence was confirmed to such an extent as it admitted of no doubt.

When the Chilean earthquake occurred, two Askania gravimeters with an automatic recording apparatus, Nos. 105 and 111, were working for the purpose of observing the tidal variation of gravity at Kyoto. Latitude, longitude and height of the observation station were 35°01.8′ N, 135°47.2′ E and 59.9 metres respectively.

Records obtained with the Askania gravimeter No. 111, being sensitivity of 2.5087 μgal/mm, were used for the present analysis to detect free oscillations of the earth. Reading of the records was made at 2-minute intervals from 04 h 00 m of May 23, 1960 (UT) up to 0.1 mm and values of 1480 readings were obtained. These read values thus obtained were filtrated by a highpass filter (29), and analysed by Fourier's method by using an electronic computing machine 'NEAC-2203'. Spectral analysis was made for ranges of wave number $n=41$ to $n=326$ corresponding to periods 66.4-minute to 8.4-minute, and its origin time was 05 h 56 m of May 23. In Fig. 6 was shown smoothed spectrum in a range of $n=40$ to $n=80$.

By the present spectral analysis, the earth's free oscillations of spheroidal modes S_0, S_2, S_3, S_4,......, S_{12} are clearly detected. Generally speaking, the obtained periods corresponding to these earth's oscillations, are in good agreement with those obtained in America and Europe, and also with periods predicted by theoretical investigations. To mention more precisely, however, the periods obtained by the present analysis seem to be a little longer than those predicted by theoreticians for the Gutenberg model (30). This may be due to a low velocity zone being near to the earth's surface under Japan (31).

The spectral peak at a period of 53.4 minutes is one corresponding to the fundamental spheroidal oscillation of the earth. The gravity variation due to this earth's free oscillation is about 0.58 μgal in amplitude and attains its negative maximum at the origin time of the earthquake, that is, 19 h 11 m of May 22, 1960 (UT). Moreover, the amplitude of vertical displacement corresponding to the gravity variation with 53.4-minute period is calculated to be about 0.52 centimetres.

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